THE DEVELOPMENT OF A STRAIN GAGE BALANCE SYSTEM FOR THE THIRTY INCH WIND TUNNEL AT THE GEORGIA SCHOOL OF TECHNOLOGY

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A THESIS

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THE DEVELOPMENT OF A STRAIN GAGE BALANCE SYSTEM FOR THE THIRTY INCH WIND TUNNEL AT THE GEORGIA SCHOOL OF TECHNOLOGY

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SUMMARY

The problem of undertaking the design of a strain gage balance system was prompted by the need of a new balance system for the thirty inch wind tunnel at the Georgia School of Technology.

A preliminary study of the uses, advantages and disadvantages of strain gages was made and at the same time preliminary sketches of the proposed system were drawn. After the preliminary studies were completed and a definite type of balance system had been decided upon, the design calculations were made and the necessary engineering drawings completed.

The system was then built, calibrated and tested. Results of tests made with Clark Y airfoil sections indicate lift and moment coefficients agree very well as compared to values taken at other wind tunnels. The drag coefficients were a vast improvement over those obtained from the wire balance system. It is hoped that still further improvement can be made. (See Conclusions and Recommendations.)

On the basis of the results obtained from the tests herein described this balance system is being adopted for student instruction. It will be used by future classes in the study of wind tunnel operations.

INTRODUCTION

The balance system used in the thirty inch wind tunnel at the Daniel Guggenheim School of Aeronautics, Georgia School of Technology, is of the wire type that was popular several years ago. Compared to present standards of accuracy required of balance systems in general, this wire type is inadequate. In comparison with the newer type balance systems this old system is relatively inaccurate in measuring the applied loads; indicates a lack of sensitiveness in the drag component of the balance; necessitates a more complicated method of mounting the model; has a large tare drag; and does not have a provision for the taking of simultaneous lift, drag and moment readings.

In recent years the wire resistance strain gage has been developed to a high state of perfection and in measuring forces is very widely used in the structural testing field. It was natural that this type of force measuring device should find its way to wind tunnel balance systems. In recent months strain gages have been used in several laboratories as force measuring devices for experimental balance systems and have found much use in supersonic work where the models are small and working space is at a minimum.

It is the purpose of the design herewith presented to provide the basis for a three component balance system to replace the three component wire system now in use. This new design, it is believed, will:

1. Measure all forces accurately with very small error.
2. Provide a simple method of model attachment.
3. Provide sensitive load change indications.
4. Provide simultaneous lift, drag and moment readings, (when a properly designed indicating unit is available).
5. Have relatively small tare drag.

One of the major problems of the strain gage type of balance system is the movement of the model from a given location in the tunnel due to the deflections of the spring arms. This deflection also causes interaction between components of the balance. For instance, a pure lift load might give drag readings.

Although the deflections of the spring arms cannot be reduced below a certain minimum, the interaction of forces has been eliminated to a great extent in this design. The deflection of the drag and moment gages tend to induce a slight change in angle of attack on the model being tested, whereas any deflection in the lift gage causes only a vertical translation of the model from one position to another.

Under the maximum design load, using the formula[1]

$$\delta = \frac{2PL^3}{3EI_o}$$

the deflection at the point of model support due to the drag gage is 0.1236 inches, which corresponds to an angle of attack change of 23.6 minutes. For the models that were tested (See Tables III and IV) only about one-sixth of the design load was realized on the drag gage. As the deflection, and thus the angle of attack change, is directly proportional to the load it is evident that for the loads herein encountered the actual change in angle of attack due to the deflection of the drag arm is of the order of 4 minutes.

Similarly the deflection of the moment gage has a slight effect on the change of angle of attack. For the maximum design load on this gage the deflection of the gage, and hence that of the after part of the model sting, is 0.078 inches. This deflection induces a maximum angle of attack change of 1^o. For this gage only one-fifth of the design load was realized from the models tested, thus reducing this angle change to approximately 12 minutes. Thus the maximum angle of attack change incurred due to the deflections of the drag and moment gages for the models tested was of the order of one quarter of a degree. This is within the accuracy with which the original angle of attack could be set.

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[1] Timoshenko, S., and Gleason H. MacCullough, "Elements of Strength of Materials", (New York: D. Van Nostrand Company, Inc., 1940), Equation (b), p. 181.

This balance system is also different from other known types of strain gage balance systems in that the model is supported in only one place with an attachment for the measurement of pitching moment in addition. Other known proposals have the model supported in three places.

No attempt has been made to design an indication unit that will give simultaneous lift, drag and moment readings as it was felt that this would be a problem in itself and therefore beyond the scope of this particular project.

DESCRIPTION OF THE BALANCE SYSTEM

General Considerations

In designing the balance system herein described four factors were considered as being the most important:

1. Uses of the system
2. Simplicity
3. Accuracy
4. Ruggedness

The thirty inch wind tunnel at the Daniel Guggenheim School of Aeronautics, Georgia School of Technology, is used primarily for student instruction in basic fundamentals of wind tunnel operation. It is known from past experience that equipment for student instruction must be durable and not easily damaged by inexperienced hands. With this thought in mind the strain gage balance system was designed to give trouble free service under rough usage over a future period of years. The main features will be discussed later.

In considering the design of the strain gage balance system several different types of balances were discussed. First it was decided to use a three component system (one that measures lift, drag and longitudinal pitching moment forces only) in favor of a six component system which, in addition to the above, measures the side force and roll on the model being tested. It was felt that the three component system would satisfy instructional requirements and that the added expense due to the complications involved, had a six component system been selected, was unjustifiable in this case. The choice of the three component system simplified the design problems considerably and also the operation of the system once it was built. Force separation was much easier for the three component system. Second, a single strut support for the model was decided on. Three general types of strain gage balances are under investigation at the National Advisory Committee for Aeronautics, Langley Memorial Laboratory, Langley Field, Virginia and some have been built and tested. From these investigations[2] it has been revealed that a strain gage balance may be located with respect to the model in three places:

1. Inside the model
2. Outside the model, but inside the tunnel
3. Outside the tunnel.

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[2] U. S. National Advisory Committee for Aeronautics, Letter dated February 3, 1947.

The first is used in supersonic model testing almost exclusively and its use here was not feasible with the type of models to be tested. The third system is not applicable to the particular tunnel for which this balance system was designed. Therefore, a system of the second type was chosen. As work has been done on a three support balance of this type, this design is based on the single strut type as it is much simpler to work with in a three component system. These simplifications have enhanced the accuracy of the system as a whole.

Before design work could begin the magnitude of forces to be measured was ascertained. From several years of previous tests on the models that are available for the thirty inch wind tunnel the following loads were chosen as the maximum loads that would be encountered on present or probable future models:

Lift force- - - - -7 lb.
Drag force- - - - -3 lb.
Pitching moment
force- - - - - - -10 in. lb.

All members of the movable part of the system, except the strain gage springs, were designed to give a minimum deflection, commensurate with size and reasonable accuracy under these maximum loads. This was done in order that the major deflections would be due only to the deflection of the strain gage springs which will be discussed later.

THE FRAME

Specifically, the frame of the strain gage balance system includes a base, a support and a linkage system which separates the lift, drag and pitching moment forces. (See Figs. 1 and 2.)

The base is a mahogany box to which is fastened the support. The base itself is easily movable and can be put in and taken out of the tunnel with very little effort. By means of four screws it can be rigidly fastened to the floor when in the tunnel. The support is made from 1 inch by 4 inch 24ST aluminum alloy bar stock and is rigidly attached to the base providing a solid foundation for the attachment of the linkage system and strain gage springs. This assures continued perfect alignment of the system after it is once assembled and aligned. This is important for duplicating results on the same model time after time and eliminates the need for continuous calibration and tare readings.

The linkage system is made up of a lift arm which is connected to the lift spring through a multiplying linkage (Fig. 1). The drag arm is connected at right angles to the lift arm and is in turn directly attached through ball bearing pivots to the drag spring. The moment spring and moment rod are attached to the after part of the lift arm. All parts are connected together with close tolerance pins through the bearings.

The lift arm is covered with a sheet metal shield which is attached to the support. This shield is cut off four inches below the point of model support leaving only the small lift arm insert to interfere with the airflow close to the model.

THE PIVOTS

The pivots in a balance system of this type are critical, especially at low loads. Low moment restraint and absolute freedom of movement are important.

An investigation was made on the use of flexure pivots in this particular balance. Of three types of flexure pivots: (1) A thin metal strip, (2) A thin wire rod, and (3) A Z-section pivot, none could be fitted or adapted to this basic design. As flexure pivots will take no transverse shear load the first and second types were excluded from the beginning. The third type has points in its favor but the cost of manufacturing this Z type of pivot was prohibitive for this project. In addition the balance would have been much larger and probably not as rugged if this pivot had been used. On the basis of these findings it was finally decided that ball bearing pivots be used. A Fafnir type K-3L Aircraft bearing was chosen as being adequate for the amount of load that would be applied. This bearing was also relatively cheap and easy to obtain.

THE STRAIN GAGE SPRINGS

The strain gage springs are the most important part of the system. Springs can be made from various materials, each having its advantages and disadvantages for this type of use. Steel, Phosphor Bronze and Structural Aluminum Alloy are three such materials. Of the three listed, Dural was chosen as it has a low modulus of elasticity and consequently gives a greater stiffness for a given strain on the gage.

The original springs were designed to produce a strain of 0.001 inch per inch under maximum load. This particular value is recommended by H. B. Edwards[3] as being the best balance between safety factor, hysteresis errors and electrical output. Edwards also points out that for the most efficient use of space and material a spring of constant stress design should be used so that each gage will be subjected to the maximum strain uniformly throughout its length. This type of spring provides greater sensitivity than one made as a constant cross section beam.

Springs of this type must be designed to cover only a limited load range. The original springs built for the system are considered accurate from twenty per cent of maximum load to maximum load. For low load values different springs should be used. However the primary purpose of the design was to test the principles involved and the refinements are left to some future date. The low load springs should be designed to produce a strain of 0.001 inch per inch under ten to thirty per cent of maximum load depending upon the accuracy desired.

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[3]Edwards, H. B., "Wire-Strain-Gage Hinge-Moment Indicators for Use in Tests of Airplane Models", (U. S. National Advisory Committee for Aeronautics Bulletin No. L4D15, April, 1945).

The springs herein employed give low deflections under maximum load and consequently cause little trouble as to change in angle of attack of the model. (See Page 5.) They are also designed so the low load springs will be readily interchangeable with the present ones. This also makes for versatility of the system as stronger springs can be made and installed should larger forces than the maximum ones herein considered be encountered in some future models.

To each spring is cemented two Baldwin Southwark SR4-A5 strain gages. The use of two gages provides automatic temperature compensation and doubles the output from each spring.

THE INDICATING SYSTEM

An SR-4 strain gage control box utilizing a 6 volt power supply provided by an automobile storage battery was used to indicate load changes on the various spring arms of the balance system. This method proved to be satisfactory for the first test results and it was found, after familiarity with the unit was obtained, that a complete test run on one gage could be made in a matter of thirty minutes. Thus in one and one half hours a complete set of data for the lift drag and moment gages could be effected.

Future work on an indicating system that will give simultaneous lift, drag and moment readings will expedite this slow process and a complete set of data can be obtained in about one third the time required for these first test results.

CALIBRATION

Upon assembly of the system each gage arm was calibrated by means of dead weights applied at the points of model support. Curves of ΔM (difference in micrometer readings from zero setting) versus load in pounds were plotted (Fig. 10). Thus with a given ΔM, the load realized may be picked off of the load calibration curve and the aerodynamic coefficients calculated. Each gage was calibrated twice during the time that tests were conducted and the second calibration duplicated the first.

TESTS AND RESULTS

A series of tests were run on two model wings with a Clark Y airfoil section, one 3" x 18" (Aspect Ratio = 6) and the other 3" x 12" (Aspect Ratio = 4). Tare runs were made on the balance without the wing and results showed that no tare load existed for the lift and moment gages but that a tare load of 0.15 lb. was present in the drag gage. This value was subtracted from drag readings to give the true drag results.

A wing was then mounted as shown in Fig. 3 and the angle of attack was varied from -6° to $+15^{\circ}$ in two degree increments. Readings were made for the positive angle of attack changes from -6° to $+15^{\circ}$ and also for the negative angle of attack changes from $+15^{\circ}$ to -6° in order to check the duplication of results and to balance out any error in the setting of the angle of attack. All results were duplicated in this manner within reasonable accuracy. As a precision inclinometer was used to set the angle of attack of the model, variations of the readings were kept at a minimum.

The tunnel was run at an indicated velocity of 88 ft/sec. which, with the models tested, corresponds to an effective Reynolds Number of 236,000. The final series of runs on each wing was made on the same day and under the same conditions in order to obtain consistent data.

The aerodynamic characteristics for each wing were calculated and plotted in Figs. 5 through 9. These results were compared with those given in several National Advisory Committee for Aeronautics Technical Reports[4].

As is indicated from the curves, the new balance system gives excellent results for lift and moment and drag results which are far superior to those obtained from the old system. These results agree closely with the values for similar airfoil sections given in the N.A.C.A. reports mentioned above. This indicates that the present system herein presented is sound and with proper refinements will far surpass the old system in the accuracy of results obtained.

From the curve of C_L vs. α , Fig. 5, it is noted that

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[4]U. S. National Advisory Committee for Aeronautics, Technical Reports 233, 244, 331 and 628.

the maximum C_L for the AR = 6 wing is not as high as that presented in the N.A.C.A. reports. However, the slope of the lift curve is the same as for the N.A.C.A. curves. That the maximum C_L was not reached indicates some irregularity in the model. It was noted during the tests that due to warping over a long period of years the wooden models used were no longer of the same airfoil shape thus making the results somewhat in error. Difference in values of $C_{M\frac{1}{4}}$ and the angle of zero lift substantiate this observation. The additional fact that the tests were run at a low Reynolds number would cause the maximum C_L to appear low as compared to tests run at a higher Reynolds number.

From the curves of C_D vs. α and C_L vs. C_D, Figs. 6 and 7 respectively, it is seen that the values obtained from tests of the new system are much closer in agreement with those values given in the N.A.C.A. reports than are the values obtained from tests with the old wire system.

From the moment coefficient curve, Fig. 9, the comparison of results from the old and new systems readily shows which is the more accurate.

One modification was made during the tests. On the first runs the model sting was connected to the moment rod by means of a bolt, but this proved unsatisfactory. A small (3/8" OD) ball bearing and close tolerance pin were used to connect this point for the final tests. After this change was made the results of the moment readings became very accurate as is shown in Fig. 9.

Throughout all runs each set of data could be duplicated time after time thus indicating that good results were not achieved by chance, but could be achieved with uniform regularity.

CONCLUSIONS

From the results of the foregoing tests it has been concluded that:

1. The strain gage balance system herein presented is of a workable nature and gives good results in its present form.

2. With suitable refinements this new system should give results comparable to any modern system now in use.

3. Deviation of test results from those presented in the N.A.C.A. Technical Reports is due, in part, to the following:

    (a) Irregularities in the models tested
    (b) Vibration at the point of model support due to play in the ball bearing
    (c) Possible drag on moment sting.

4. The new system gives much better results than the old wire system.

5. The drag gage shows a sensitivity that is not apparent in the old system.

6. Tare values are lower for the new system.

7. The gage springs give fairly good results at low loads and excellent results at high loads.

8. Test data for any one model can be duplicated time after time as desired.

RECOMMENDATIONS

For future refinements to perfect the basic system it is recommended that:

1. New models be made from either magnesium or aluminum so that the true airfoil shape will be maintained under all conditions.

2. These new models be mounted in a method different from that used at present. Specifically, miniature ball bearings should be utilized and two of them used to mount a wing, thus reducing model vibration to a minimum. All exterior brackets should be removed and the attachment point located inside the model if at all possible.

3. The streamlined shield should be enlarged to enclose the moment rod in order to reduce drag tare. This will probably reduce vibration of the model as some buffeting of moment rod at rear of shield was noted.

4. The size of the spring that measures the drag should be reduced when wing models alone are tested as the drag of a model wing is much lower than the maximum load for which the gage is designed.

5. An indicating unit that will give simultaneous lift, drag and moment readings should be built. One possibility is the use of a switching unit and a series of self-balancing bridge circuits that could all be set to the same zero. Thus,

by switching from one gage to another and changing the micrometer on the SR-4 strain gage control box, a series of lift, drag and moment readings could be made at the same angle of attack at the same time.

6. Models should be designed to be mounted upright or inverted.

7. Moment sting should be improved to reduce interaction between sting and model.

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APPENDIX

SAMPLE CALDULATIONS

Lift

For an angle of attack $\alpha = 4^{\circ}$ the micrometer reading on the control box was $M = 6.05$. The no load reading was $M_{nl} = 1.66$

$$\Delta M = M - M_{nl}$$
$$\Delta M = 6.05 - 1.66$$
$$\Delta M = 4.39$$

Entering the calibration curve at $\Delta M = 4.39$ a load $L = 2.28$ lbs. is obtained. From the well known lift formula C_L is obtained.

$$C_L = \frac{L}{qS}$$

where $q = \rho/2V^2$ and S = wing area in ft.^{2}.

The average density ρ for Atlanta, Georgia is 0.00222 slugs/ft.^{3}

$V = 88$ ft./sec. Thus $q = \frac{.00222}{2}(88)^2$ and qS for an $AR = 6$ (3" x 18") wing is $qS = \frac{.00222}{2}(88)^2\left(\frac{54}{144}\right) = 3.22$

Therefore $C_L = \frac{2.28}{3.22} = 0.708$

Angle of Attack Correction

The true angle of attack α_F° is given by

$\alpha_F^{\circ} = \alpha^{\circ}_{measured} + 0.5^{\circ} + \Delta\alpha^{\circ}$ where 0.5° is the angle of the airstream upflow in the tunnel and $\Delta\alpha^{\circ}$ is the correction for an open jet and is given as $\Delta\alpha^{\circ} = \delta \frac{S}{C} C_L(57.3)$ where $\delta = -.14$ for the tunnel considered here and S = wing area in square inches.

$C = 900$ in.^{2} = test section area in square inches.

For an α° measured of 4°, α° measured $+ 0.5^\circ = 4.5^\circ$

$$\Delta\alpha^\circ = (-.14)\left(\frac{54}{900}\right)(.708)(57.3)$$

$$\Delta\alpha^\circ = -.481\ (.700)$$

$$\Delta\alpha^\circ = -.341^\circ$$

$$\alpha_F^\circ = 4.5 - .341 = 4.159^\circ$$

<u>Drag</u>

At α° measured $= 4^\circ$ and $M_{n1} = 3.40$, $M = 4.88$, and

$M = 4.88 - 3.40 = 1.48$, $D = .31$ lb., drag tare $= .15$ lb.

$D^1 = D - \text{tare} = .31 - .15 = D^1 = .16$ lb.

From the drag formula $C_D1 = \frac{D^1}{qS}$

$$C_D1 = \frac{.16}{3.22} = .0498$$

The drag correction due to open jet is given as

$$\Delta C_D = \delta\ \frac{S}{C}\ C_L{}^2 = -.14\left(\frac{54}{900}\right)C_L{}^2 = -.0084\ C_L{}^2$$

Corresponding to α°measured $= 4^\circ$, $C_L = .708$ and $C_L{}^2 = .500$

Thus $\Delta C_D = -.0084\ (.500) = -.0042$

$$C_D = C_D1 + \Delta C_D = .0498 - .0042 = .0456$$

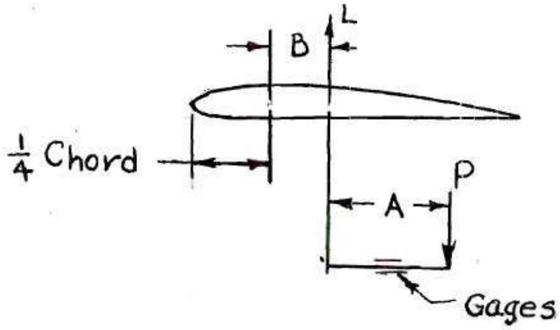
<u>Profile Drag Coefficient</u>

$C_D = C_{Do} + C_{Di}$ where $C_{Di} = \frac{C_L{}^2}{AR}(1 + S)$ where $S = .054$ for $AR = 6$ and $S = .033$ for $AR = 4$

$$C_{Di} = \frac{C_L{}^2}{6}(1.054) = \frac{.500}{6}(1.054) = .0279$$

$$C_{Do} = C_D - C_{Di} = .0456 - .0279 = .0177$$

<u>Moment Coefficient About the Quarter Chord</u>



A = 3.25 in.

B = 0.75 in.

A + B = 4 in.

= .333 ft.

Considering positive moments as being clockwise

$$M_{\frac{1}{4}} = P(A + B) - L(B)$$

For $\alpha^\circ = 4^\circ$ on the AR = 6 model, P = .260 lb.

$$P(A + B) = (.260)\ (.333) = .0865 \text{ ft. lb.}$$

$$L = 2.28 \text{ lb.},\ L(B) = 2.28(\frac{.75}{12}) = 2.28(.0625)$$

$$L(B) = .1425 \text{ ft. lb.}$$

$$M_{\frac{1}{4}} = .0865 - .1425 = -.0560$$

$$C_{M1/4} = \frac{M\ 1/4}{qSC}$$ where C = .25 ft., the chord

of the model.

$$C_{M1/4} = \frac{-.0560}{322(.25)} = -.0695$$

All calculations for the AR = 4 wing are made similarly.

TABLE I

LIFT DATA

ASPECT RATIO = 6

DECADE- - - - - - - - - 5000
SENSITIVITY - - - - - HIGH
SHUNT REVERSED
IN BALANCE - - - - - 1.66

α°	M	ΔM	L	C_L	α_1°	$\Delta\alpha^\circ$	α_F°
-6	1.55	-.11	-.06	-.0186	-5.5	+.0089	-5.49
-4	2.50	.84	.43	.1335	-3.5	-.0628	-3.56
-2	3.34	1.68	.86	.2670	-1.5	-.1283	-1.63
0	4.28	2.62	1.36	.4220	.5	-.2030	.297
2	5.20	3.54	1.85	.5750	2.5	-.2760	2.224
4	6.05	4.39	2.28	.7080	4.5	-.3410	4.159
6	6.83	5.17	2.68	.8330	6.5	-.4000	6.100
8	7.52	6.86	3.05	.948	8.5	-.4550	8.045
10	8.08	6.42	3.36	1.042	10.5	-.5020	10.000
12	8.38	6.72	3.51	1.090	12.5	-.5250	11.475
14	8.05	6.39	3.33	1.033	14.5	- .497	14.003
15	7.26	5.60	2.91	.904	15.5	-.435	15.065

TABLE II

LIFT DATA

ASPECT RATIO = 4

DECADE - - - - - - - - - 5000
SENSITIVITY - - - - - HIGH
SHUNT REVERSED - - - - - - -
IN BALANCE - - - - - - - 1.87

$\alpha°$	M	ΔM	L	C_L	$\alpha_1°$	$\Delta\alpha°$	$\alpha_F°$
-6	1.47	-.40	-.20	-.0934	-5.5	+.0299	-5.471
-4	2.02	.15	.075	.035	-3.5	-.0112	-3.511
-2	2.51	.64	.32	.149	-1.5	-.0479	-1.548
0	3.10	1.23	.64	.298	0.5	-.0957	.404
2	3.55	1.68	.85	.396	2.5	-.1270	2.373
4	4.12	2.25	1.17	.545	4.5	-.1750	4.325
6	4.57	2.70	1.40	.653	6.5	-.2095	6.290
8	5.11	3.24	1.67	.780	8.5	-.250	8.250
10	5.55	3.68	1.91	.891	10.5	-.286	10.214
12	6.03	4.16	2.16	1.009	12.5	-.323	12.180
14	6.25	4.38	2.28	1.063	14.5	-.342	14.158
15	6.28	4.41	2.30	1.072	15.5	-.344	15.156
15.75	6.05	4.18	2.17	1.011	16.25	-.3246	15.925

TABLE III

DRAG DATA

ASPECT RATIO = 6

DECADE- - - - - - - - - 4600
SENSITIVITY - - - - - - HIGH
SHUNT REVERSED
IN BALANCE - - - - - 3.40
TARE DRAG - - - - - - - 0.15 lb.

α°	α_F°	M	ΔM	D	D'	C_D'	C_D
-6	-5.49	4.31	.91	.20	.05	.01551	.0155
-4	-3.56	4.29	.89	.19	.04	.01242	.0122
-2	-1.63	4.32	.92	.20	.05	.0155	.0149
0	.297	4.51	1.11	.24	.09	.0280	.0265
2	2.224	4.66	1.26	.26	.11	.0342	.0314
4	4.159	4.88	1.48	.31	.16	.0498	.0456
6	6.100	5.14	1.74	.37	.22	.0684	.0626
8	8.045	5.39	1.99	.43	.28	.0870	.0795
10	10.000	5.70	2.30	.50	.35	.1089	.0998
12	11.475	5.96	2.56	.55	.40	.1241	.1142
14	14.003	6.81	3.41	.75	.60	.1864	.1775
15	15.065	7.62	4.22	.91	.76	.236	.2291

TABLE IV

DRAG DATA

ASPECT RATIO = 4

DECADE- - - - - - - - - - 4600
SENSITIVITY - - - - - - - HIGH
SHUNT REVERSED
IN BALANCE - - - - - - - 3.39
TARE DRAG- - - - - - - - 0.15 lb.

α°	α_F°	M	ΔM	D	D'	C_D'	C_D
-6	-5.471	4.27	.88	.19	.04	.0186	.01812
-4	-3.511	4.23	.84	.18	.03	.0140	.0140
-2	-1.548	4.23	.84	.18	.03	.0140	.01388
0	.404	4.30	.91	.20	.05	.0233	.0228
2	2.373	4.39	1.00	.21	.06	.0280	.02712
4	4.325	4.525	1.13	.25	.10	.0466	.0449
6	6.290	4.66	1.27	.27	.12	.0560	.0536
8	8.250	4.81	1.42	.30	.15	.0700	.0667
10	10.214	5.06	1.67	.35	.20	.0931	.0887
12	12.180	5.27	1.87	.40	.25	.1164	.1107
14	14.158	5.50	2.11	.45	.30	.140	.1337
15	15.156	5.68	2.29	.50	.35	.163	.1565

TABLE V

MOMENT DATA

ASPECT RATIO = 6

DECADE- - - - - - - - - - - - 4800
SENSITIVITY - - - - - - - - HIGH
SHUNT REVERSED
IN BALANCE- - - - - - - - - 3.76

α°	M	Δ M	P	P(a+b)	Lb	Mom.	$C_{M_{\frac{1}{4}}}$
-6	4.37	-.61	-.154	-.0513	.0037	-.0476	-.0592
-4	4.02	-.26	-.065	-.0216	-.0262	-.0478	-.0593
-2	3.68	.08	.022	.0073	-.0537	- .0464	-.0575
0	3.39	.37	.094	.0313	-.0850	-.0537	-.0667
2	3.04	.72	.180	.0600	-.1156	-.0556	-.0690
4	2.72	1.04	.260	.0865	-.1425	-.0560	-.0695
6	2.42	1.34	.336	.1120	-.1675	-.0555	-.0689
8	2.12	1.64	.410	.1366	-.1908	-.0542	-.0672
10	1.87	1.89	.475	.1580	-.2100	-.0520	-.0645
12	1.73	2.03	.508	.1691	-.2190	-.0500	-.0620
14	2.02	1.74	.436	.1452	-.2080	-.0630	-.0781

TABLE VI

MOMENT DATA

ASPECT RATIO = 4

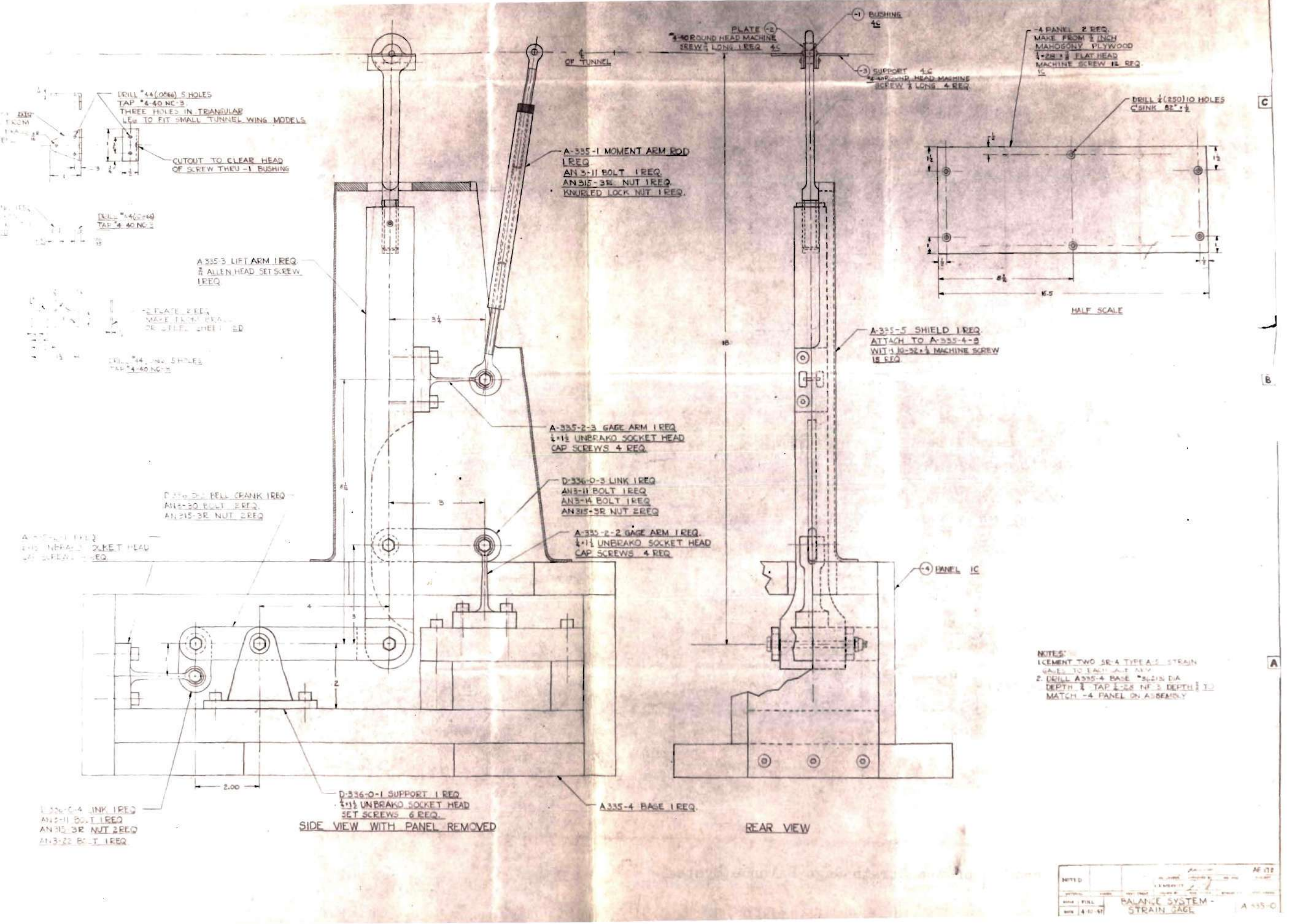
DECADE- - - - - - - - - - - - 4700
SENSITIVITY - - - - - - - - HIGH
SHUNT REVERSED
IN BALANCE - - - - - - - - 1.66

$\alpha°$	M	ΔM	P	P(a+b)	Lb	Mom.	$C_{M\frac{1}{4}}$
-6	2.06	-.40	-.39	-.1298	---	---	---
-4	1.89	-.22	-.05	-.0166	-.0047	-.0213	-.0398
-2	1.66	---	---	---	-.0218	-.0177	-.0405
0	1.49	.18	.04	.0133	-.0460	- .0327	-.061
2	1.26	.41	.10	.0333	-.0531	-.0200	-.0373
4	1.10	.57	.14	.0466	- .0731	-.0265	-.0495
6	.925	.745	.175	.0582	-.0875	-.0293	-.0547
8	.755	.915	.225	.0749	-.1041	-.0292	-.0545
10	.580	1.09	.270	.0898	-.1192	-.0294	-.0549
12	.430	1.24	.310	.1030	-.1350	-.0320	-.0597
14	.300	1.37	.340	.1130	-.1425	-.0295	-.0550
15	.270	1.40	.350	.1163	-.1439	-.0276	-.0515

TABLE VII

CORRECTION OF C_D TO INFINITE ASPECT RATIO

ASPECT RATIO = 4			ASPECT RATIO = 6		
C_L	C_D	C_{D_0}	C_L	C_D	C_{D_0}
-.093	.0181	.0174	-.0186	.0155	.0155
.035	.0140	.0139	.1335	.0122	.0112
.149	.0139	.0121	.2670	.0149	.0110
.298	.0228	.0155	.4220	.0265	.0166
.396	.0271	.0142	.5750	.0314	.0130
.545	.0449	.0205	.7080	.0456	.0177
.653	.0536	.0186	.8330	.0626	.0240
.780	.0667	.0181	.9480	.0795	.0294
.891	.0887	.0235	1.042	.0998	.0392
1.009	.1107	.0269	1.090	.1142	.0471
1.063	.1337	.0407	1.033	.1775	.1180
1.072	.1565	.0619	.904	.2291	.1835



-1 BUSHING 4C
PLATE -2
4-40 ROUND HEAD MACHINE SCREW ½ LONG 1 REQ. 4C
-3 SUPPORT 4C
ROUND HEAD MACHINE SCREW ⅜ LONG 4 REQ.
℄ OF TUNNEL
-4 PANEL 2 REQ.
MAKE FROM ⅜ INCH MAHOGONY PLYWOOD
¼-28 × ⅜ FLAT HEAD MACHINE SCREW 12 REQ.
1C
DRILL ¼ (.250) 10 HOLES C'SINK 82° × ½
HALF SCALE
DRILL #44 (.0860) 5 HOLES
TAP #4-40 NC-3
THREE HOLES IN TRIANGULAR LEG TO FIT SMALL TUNNEL WING MODELS
CUTOUT TO CLEAR HEAD OF SCREW THRU -1 BUSHING
A-335-1 MOMENT ARM ROD 1 REQ.
AN 3-11 BOLT 1 REQ.
AN 315-3R NUT 1 REQ.
KNURLED LOCK NUT 1 REQ.
A 335-3 LIFT ARM 1 REQ.
⅛ ALLEN HEAD SET SCREW 1 REQ.
A-335-5 SHIELD 1 REQ.
ATTACH TO A-335-4-B WITH 10-32 × ½ MACHINE SCREW 18 REQ.
A-335-2-3 GAGE ARM 1 REQ.
¼ × 1½ UNBRAKO SOCKET HEAD CAP SCREWS 4 REQ.
D-336-0-3 LINK 1 REQ.
AN3-11 BOLT 1 REQ.
AN3-14 BOLT 1 REQ.
AN315-3R NUT 2 REQ.
AN3-30 BOLT 2 REQ.
AN 315-3R NUT 2 REQ.
A-335-2-2 GAGE ARM 1 REQ.
¼ × 1½ UNBRAKO SOCKET HEAD CAP SCREWS 4 REQ.
-4 PANEL 1C
AN3-11 BOLT 1 REQ.
AN315-3R NUT 2 REQ.
D-336-0-1 SUPPORT 1 REQ.
¼ × 1½ UNBRAKO SOCKET HEAD SET SCREWS 6 REQ.
A335-4 BASE 1 REQ.
SIDE VIEW WITH PANEL REMOVED
REAR VIEW
NOTES:
1. CEMENT TWO SR-4 TYPE A-1 STRAIN GAGES TO EACH GAGE ARM.
2. DRILL A335-4 BASE DIA DEPTH ⅞ TAP ¼-28 NF-3 DEPTH TO MATCH -4 PANEL ON ASSEMBLY
BALANCE SYSTEM - STRAIN GAGE
A-335-0

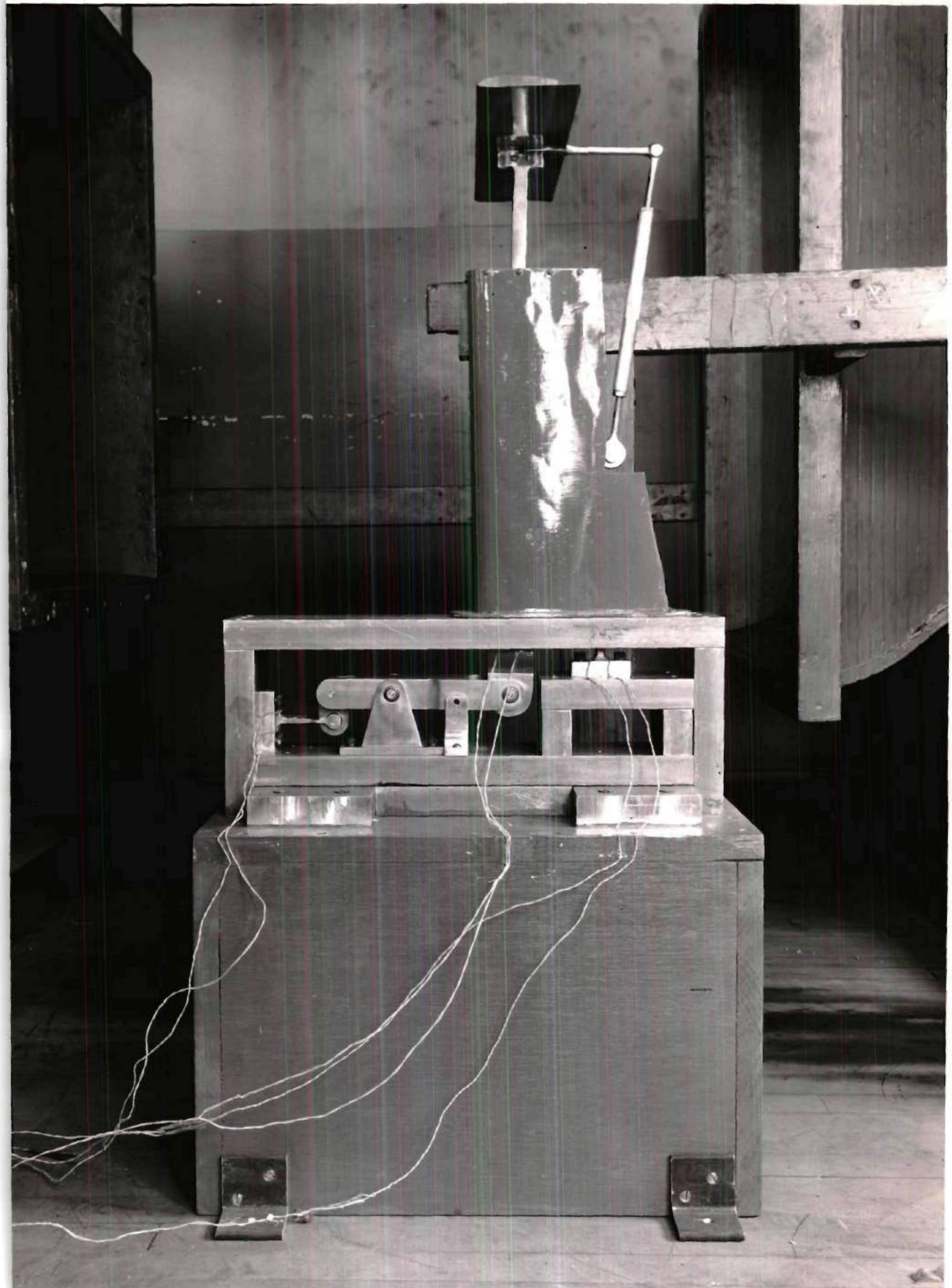


Figure 2 - Side View of the Strain Gage Balance System

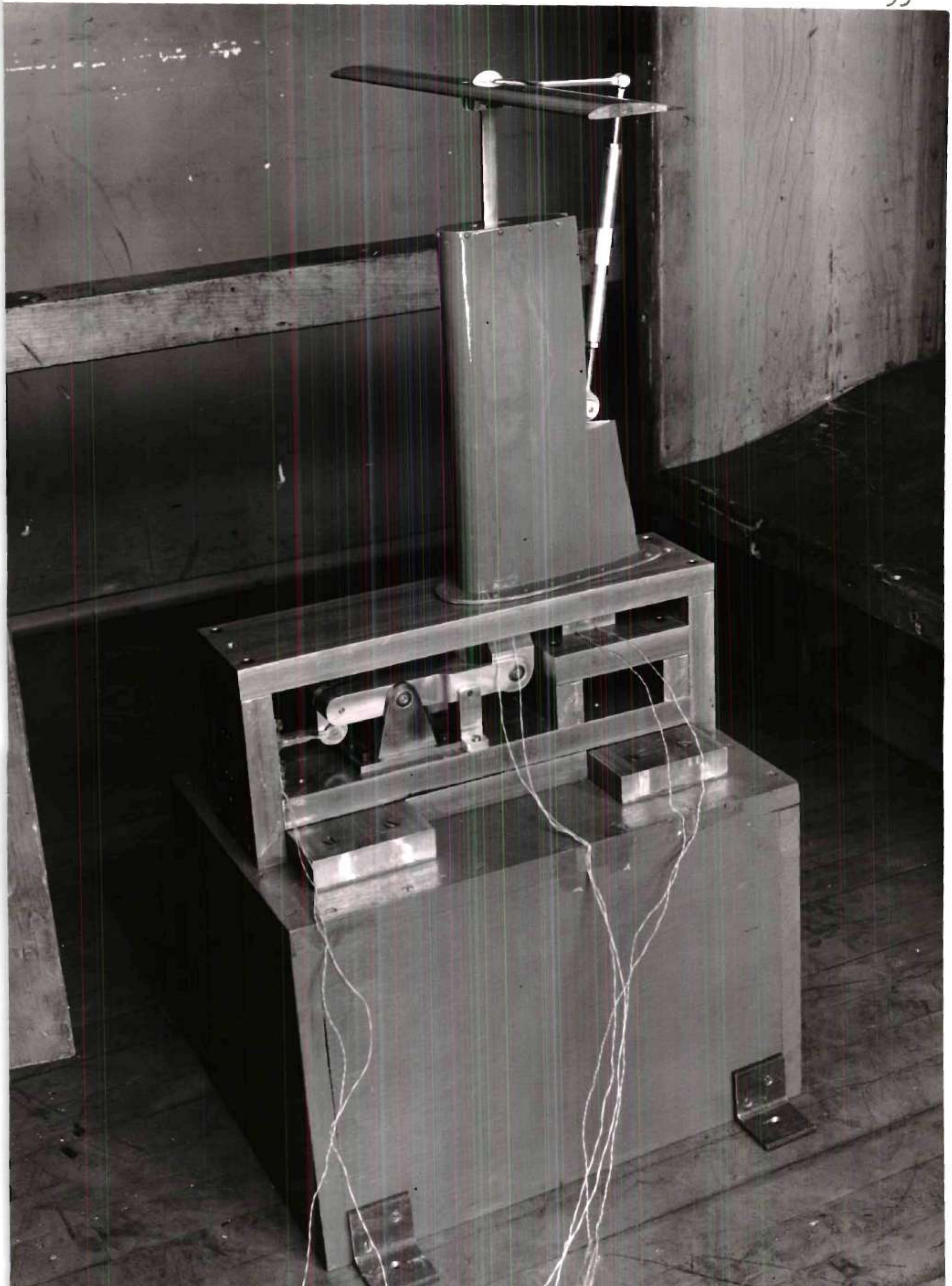


Figure 3 - The Strain Gage Balance System in the Tunnel

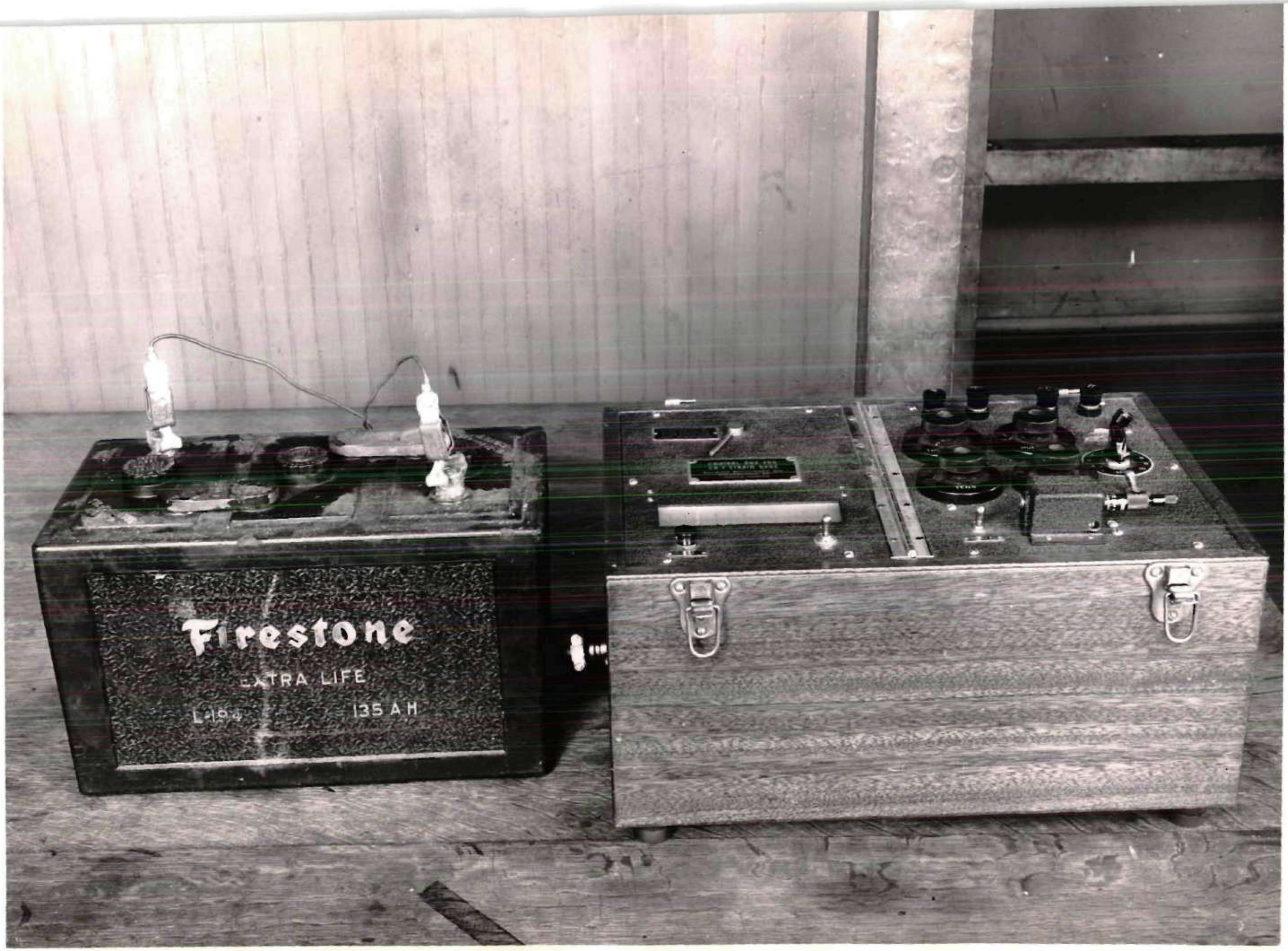
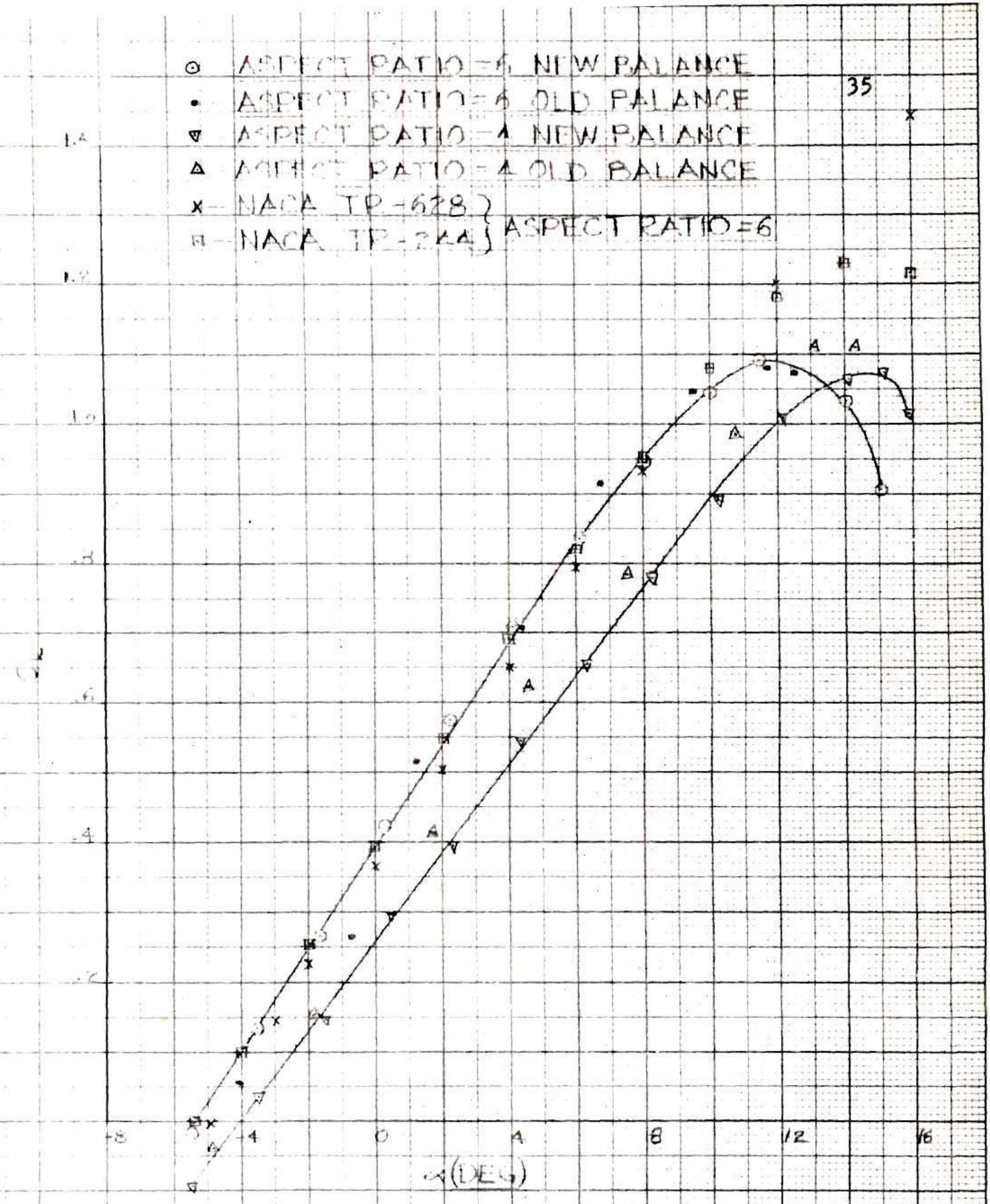
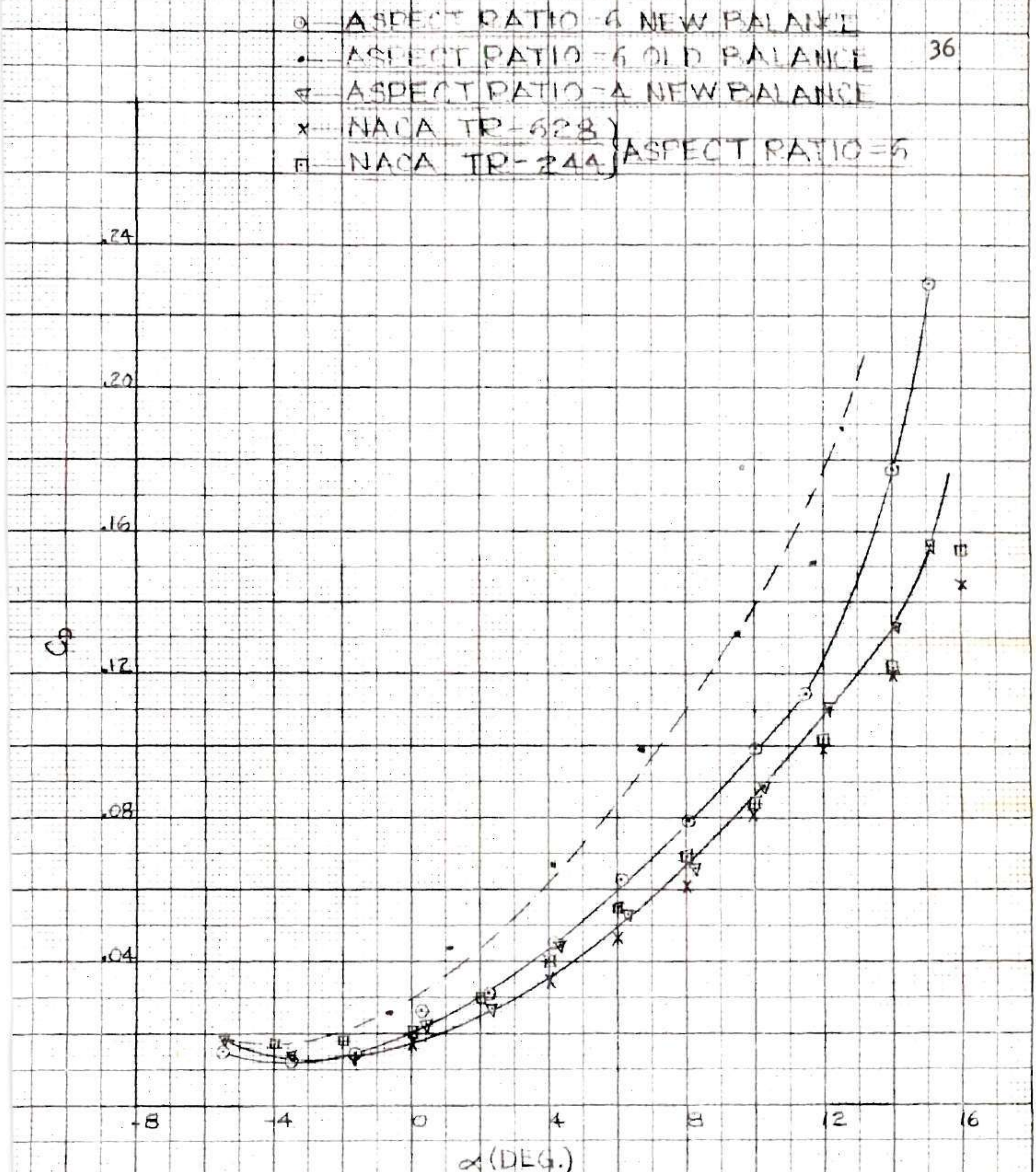


Figure 4 - The SR-4 Strain Gage Control Box



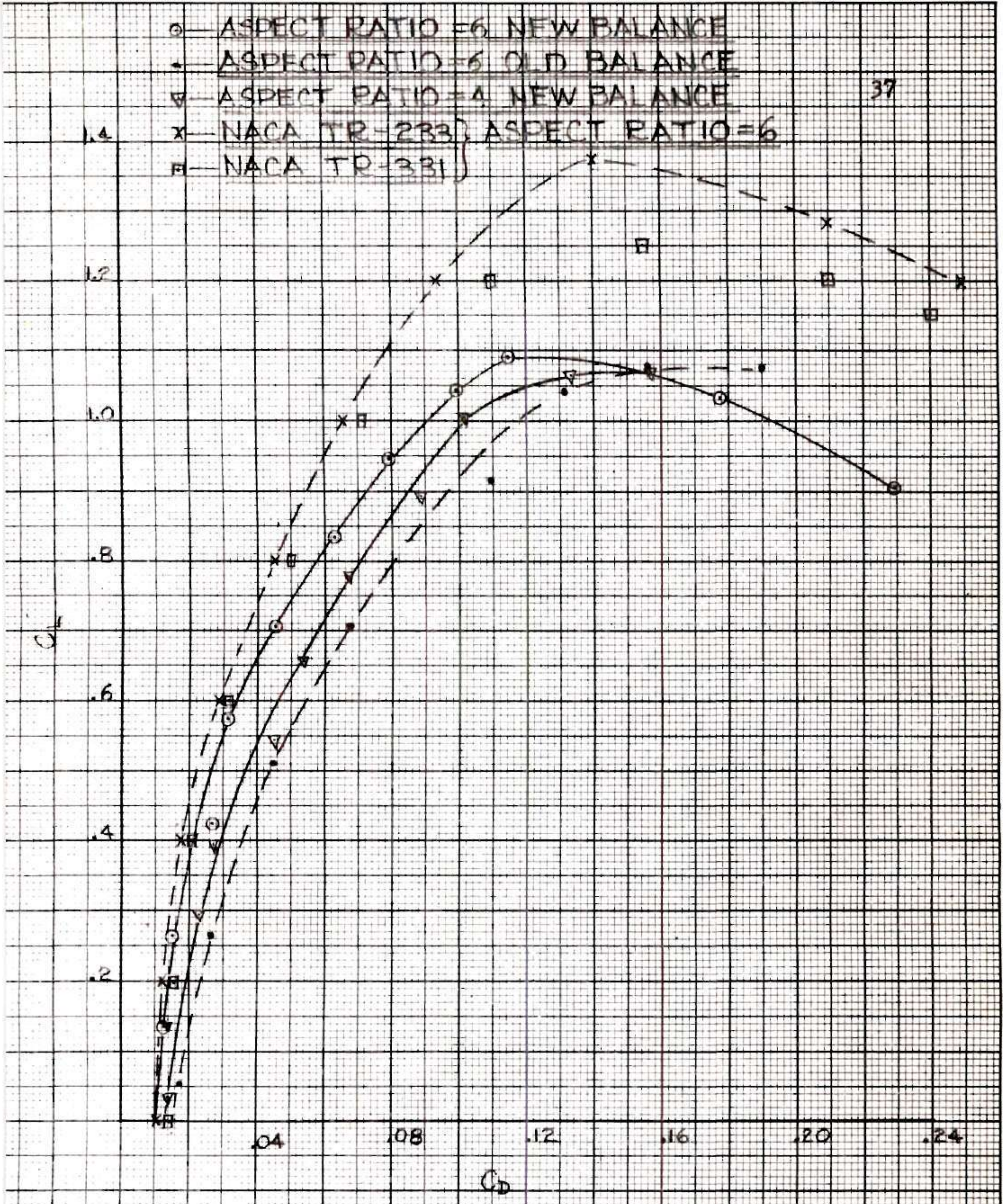
VARIATION OF C_L WITH α

FIG. 5



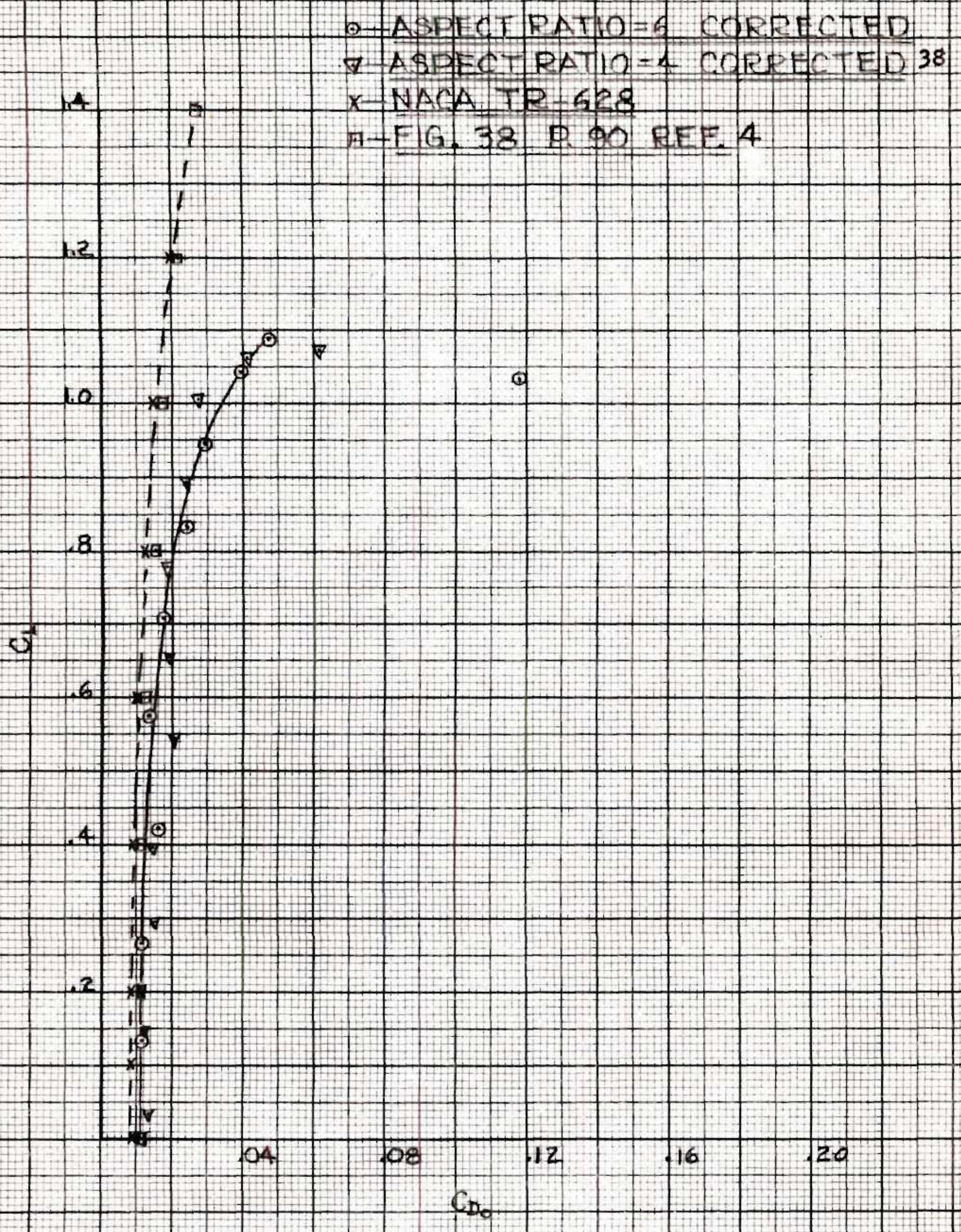
VARIATION OF C_D WITH α

FIG. 6



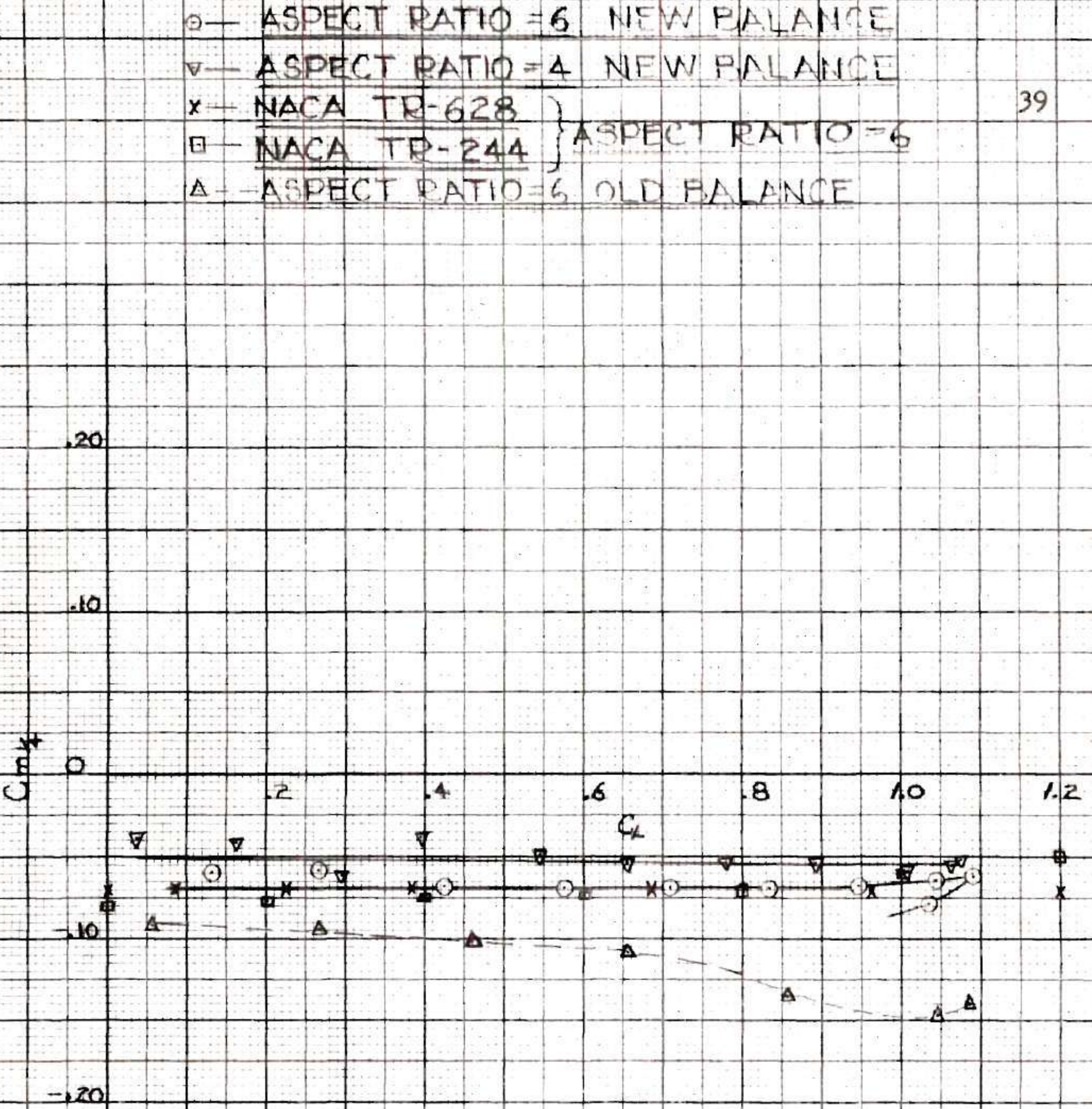
VARIATION OF C_L WITH C_D

FIG. 7



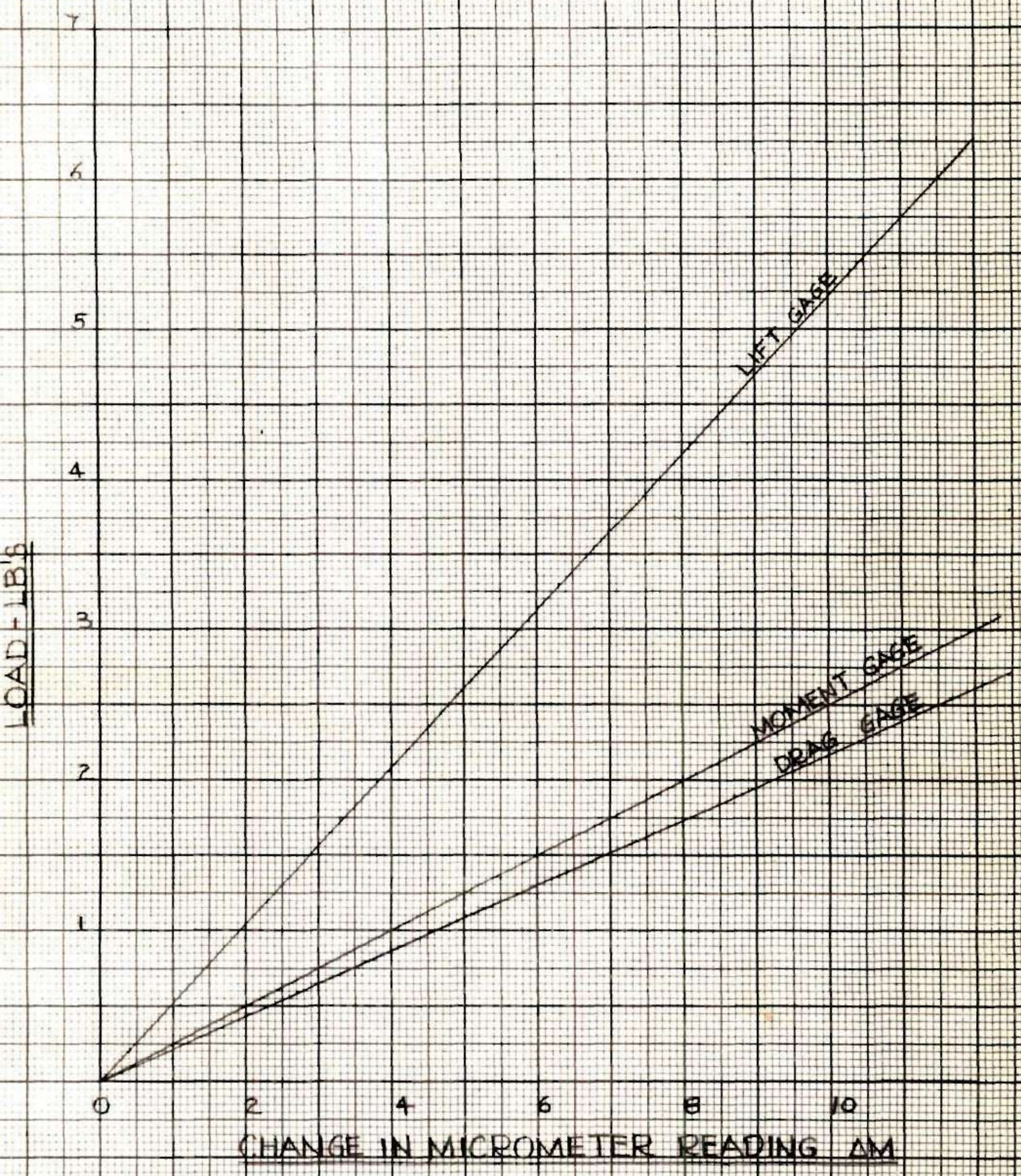
VARIATION OF C_L WITH
PROFILE DRAG COEFFICIENT C_{D_0}

FIG. 8



VARIATION OF
MOMENT COEFFICIENT, $C_{M\frac{1}{4}}$
WITH C_L

FIG. 9



CALIBRATION CHART FOR
LIFT, DRAG, AND MOMENT
GAGES
FIG. 10